

Optimization of the Series-HEV Control with Consideration of the Impact of Battery Cooling Auxiliary Losses

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ABSTRACT

This paper investigates the impact of battery cooling ancillary losses on fuel economy, and optimal control strategy for a series hybrid electric truck with consideration of cooling losses. Battery thermal model and its refrigeration-based cooling system are integrated into vehicle model, and the parasitic power consumption from cooling auxiliaries is considered in power management problem. Two supervisory control strategies are compared. First, a rule-based control strategy is coupled with a thermal management strategy; it controls power system and cooling system separately. The second is optimal control strategy developed using Dynamic Programming; it optimizes power flow with consideration of both propulsion and cooling requirement. The result shows that battery cooling consumption could cause fuel economy loss as high as 5%. When dynamic programming coordinates control of the powertrain and the cooling system in an optimal way, the fuel consumption penalty due to cooling losses is reduced to 3.7%, and battery duty cycle becomes milder. Finally, rules are extracted from the optimal strategy, and a refined rule-based strategy is presented.

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INTRODUCTION

Vehicle electrification has shown great potential for reducing fuel consumption and pollutant emissions. The main mechanisms for improving vehicle fuel efficiency are: (i) regeneration, due to the presence of a reversible secondary power source and energy storage, (ii) optimization of engine operation, (iii) engine down-sizing, and (iv) possibility for engine shut-downs. All these mechanisms bring significant benefits for improving vehicle efficiency, but increase complexity; since vehicle can be driven by engine, electric system, or their combination.

In particular, a series hybrid electric vehicle (S-HEV) offers ultimate freedom in controlling engine operation, and maximum regeneration capability, due to generous size of traction motor(s). However, such a freedom creates a challenge to find the most efficient way to control hybrid powertrain system, as the conventional wisdom of operating the engine at the "sweet spot" may not be the best for the system [1, 2]. In addition, the application of the Series HEV concept to a heavy off-road vehicle imposes extraordinary power requirements and severe

load cycles on electric components, such as batteries and electric motors. Both require cooling, and in case of the battery pack, requirement for safe operation in extreme ambient conditions mandates application of a refrigerant-based cooling. This leads to high auxiliary losses; hence, the basic premise of this work is that the battery cooling losses need to be addressed in the optimization of the vehicle power management strategy.

This study focuses on the off-road series hybrid electric truck, designed to provide outstanding mobility and satisfy duty cycles under extreme ambient conditions. The chosen platform is 14t truck with 4x4 propulsion using four independent in-hub motors to enable outstanding maneuverability. The diesel engine in the truck is rated at 330 kW, and battery capacity is 9 kW-h. Given the series configuration, traction force is provided exclusively by e-motors, and either the engine or the battery is expected to provide full electrical current on-demand.

Supervisory controller coordinates operation of components in the powertrain system depending on driver commands and system states. It is critical for achieving the maximum benefits

of any given hardware. A significant body of work on supervisory control strategies for hybrids has been published, and it can be grouped in several categories. First category are heuristic-based strategies [1, 3, 4], which in case of the S-HEV establish rules for controlling the State-Of-Charge (SOC), and recharging. It is robust and simple to implement, but the efficiency performance relies highly on engineer's experience and vehicle duty cycle. To explore hybrids' full potential, algorithms for developing optimal control are adopted to minimize fuel consumption.

The best known off-line optimization approaches are dynamic programming (DP) [5, 6, 7], stochastic dynamic programming (SDP) [8, 9], and equivalent consumption minimization strategy (ECMS) [10]. Dynamic programming is used to generate the optimal benchmark. SDP strategy is sub-optimal, but can be used for real-time application, as it obtains time-invariant control strategy by solving an infinite-horizon optimization problem over the probability density function of future driving mission. ECMS is also suboptimal, and it is further developed [11, 12, 13] for real-time implementation by adjusting the equivalence factor on-line according to the driving cycle prediction, or driving pattern recognition. Model Predictive Control (MPC) strategy [14] runs optimal algorithm online over the predicted future driving conditions. Most control algorithms focus on minimizing fuel consumption as a single objective; additional attributes, e.g. reducing pollutant emissions [15] or extending battery lifespan [16, 17] are considered, and tradeoffs between fuel consumption have been demonstrated. As an example, a novel Neuro-DP approach was proposed by to handle both the high efficiency and low emissions goals [18]. However, while outstanding progress has been made with development and refinement of algorithms for maximizing the fuel economy, most optimal control strategies assume that components operate under thermal equilibrium condition or ignore the cooling system.

In case of heavy off-road vehicles such as tactical trucks, battery thermal management has been identified as a critical issue with respect to vehicle endurance and reliability [19]. Battery generates significant amounts of heat under aggressive duty cycles mainly due to its internal resistance. The heat accumulation can cause a rapid increase of temperature in battery core; as a minimum this accelerates battery aging, but in the extreme it will lead to thermal runaway that may cause the battery cell to catch fire or to explode [20]. Certain amount of power is required to remove heat from the battery pack, and since recommended safe temperature for the Li-Ion is only 55 °C, the ancillary loss can be quite high for extremely hot ambient conditions. This is significant enough to impact fuel economy [21]. Goal of this paper is to integrate the battery cooling system into the vehicle model, and optimize the operation of the Vehicle Power System based on both propulsion and thermal management energy consumption.

The original contributions of this paper are: (i) integration of the high-fidelity battery cooling model into the S-HEV powertrain system to create a Vehicle Power System (VPS), (ii)

quantification of the auxiliary power consumption for battery cooling and its impact on vehicle fuel economy over a severe driving cycle, and (iii) methodology for applying the Dynamic Programming to optimize the complete VPS, with the goal of reducing the fuel economy penalty due to battery cooling.

The paper is organized as follows. Next section describes the integrated simulation model of series HEV and quantification of the ancillary losses due to battery cooling. Section 3 proposes two control strategies, first the baseline, thermostatic SOC strategy, and secondly the optimal controller generated through application of Dynamic Programming (DP). The following section analyzes how the parasitic losses due to battery cooling impact optimal control strategy, and offers insights that are subsequently used to develop a refined, real-time implementable strategy. The paper ends with conclusion and suggests future work.

VEHICLE CONFIGURATION AND SIMULATION MODEL

This section describes the configuration of a series hybrid electric vehicle with four in-hub motors and its simulation model. Series HEVs have great benefit of reducing fuel consumption, improving packaging efficiency, extending silent operation, and onboard power [19]. Figure 1 shows the power flow diagram. The primary power source for vehicle traction is the power pack consisting of internal combustion engine coupled with generator; engine has no mechanical connection with wheels, and this brings full flexibility of engine operation control. Battery is integrated to provide bidirectional power flow, and the cooling system keeps the battery pack within desired temperature range. Four in-hub electric motors are incorporated into wheels and provide traction power exclusively. During braking, electric machines work as generators and convert braking power to electric power. All power flows are integrated via a powerbus. Supervisory controller aims to minimize the energy consumption by controlling the power flow in the powertrain system. It receives driver's command, and sends commands to all components based the embedded supervisory control strategy. Table 1 shows the vehicle specifications. Powertrain is designed to handle heavy-duty driving at 49°C ambient temperature.

Table 1. Series HEV Specifications.

Component	Specification
Vehicle	Hybridized mid-size Truck
Vehicle Weight	14,000 kg
Frontal Area	5.72 m ² (Width/Height: 2.49/2.7 m)
Engine	I8 Turbo-Diesel Engine: 330 kW
Generator	Permanent Magnet: 330 kW
Battery	Li-ion Battery Pack: 9 kWh
Motors	Permanent Magnet: 4*95 kW (Continuous)

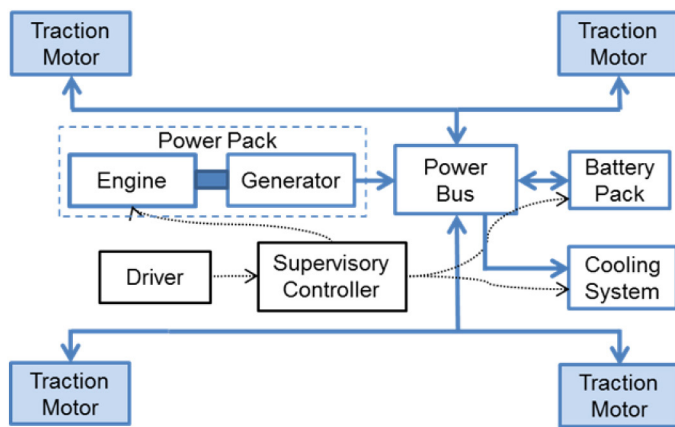


Figure 1. Series HEV powertrain configuration. Blue solid lines show the power flow, and black dot lines show the control signal flow.

Vehicle simulation model is created using a Matlab/Simulink and AMESim co-simulation arrangement (shown in Figure 2). Driver, supervisory controller, and the power system (include power pack, battery, in-hub motors, and powerbus) are modeled in Simulink; the battery cooling system is modeled in AMESim and embedded into Simulink model using the AMESim-Simulink interface.

The mechanism of battery heat generation and cooling model is illustrated in Figure 3. Cylindrical battery's thermal behavior is modeled with two states (core temperature T_c and surface temperature T_s) [22]. Heat (Q_1) is generated in battery core, and transferred to the surface (Q_2). Recirculating cooling air,

which is moved by the air pump, removes heat (Q_3) from battery surface, and then rejects it to the coolant in the evaporator. The compressor provides the required coolant flow rate; compressor mechanical power is transferred to the coolant to increase pressure and temperature. Heat is finally rejected into the environment by the condenser, and condenser fan provides flow of ambient air.

A model predictive control (MPC) strategy is integrated into the supervisory controller to control the cooling system. The controller tracks the temperature of cooling air flow, and gives power command to the condenser unit. This controller is designed based on battery duty cycle, and optimized to balance power consumption and battery temperature stability.

The fully integrated AMESim predictive model of the battery cooling system, with its own MPC controller, enables accurate prediction of battery cooling load for system-level study. It is used for couple of different purposes in this study, namely: (i) assessing the impact on S-HEV fuel economy when used in conjunction with a Thermostatic SOC, (ii) characterizing the energy loss for battery thermal management and generating a simplified model necessary for inclusion of cooling loss into dynamic programming optimization, and (iii) final validation of the cooling loss reduction with DP-optimized supervisory control. In case of (iii), the MPC controller is overridden by the optimal strategy developed for the vehicle level. Details pertaining to supervisory control development are discussed in the next section.

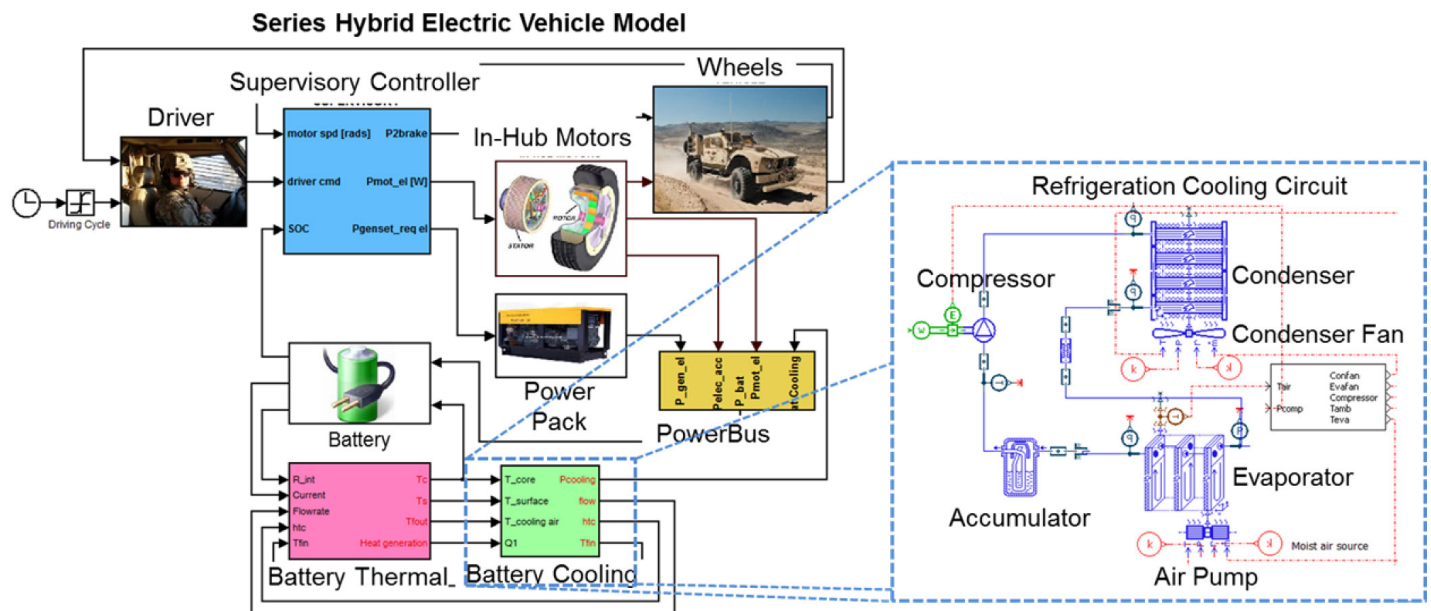


Figure 2. High-Fidelity Vehicle Model with Integration of Battery Thermal Model and Cooling System.